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Indian Standard

THREE PHASE CAGE INDUCTION MOTORS WHEN FED FROM IGBT CONVERTERS — APPLICATION GUIDE

ICS 29.160.30

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June 2009 Price Group 7

Indian Standard

THREE PHASE CAGE INDUCTION MOTORS WHEN FED FROM IGBT CONVERTERS — APPLICATION GUIDE

1 SCOPE

This standard deals with the steady-state operation of cage induction motors, when fed from IGBT converters. It covers the operation over the whole speed setting range, but does not deal with starting or transient phenomena.

The standard is applicable for low and medium voltage (up to 690 V) three phase motors manufactured up to 400 frame, and having a slip at rated load less than 5 percent.

2 REFERENCES

The following standards contain provision, which through reference in this text, constitute provisions of this standard. At the time of publication, the editions indicated were valid. All standards are subject to revision and parties to agreements based on this standard are encouraged to investigate the possibility of applying the most recent editions of the standards indicated below:

IS No.	*Title*
12065 : 1987	Permissible limits of noise level for rotating electrical machines
12075 : 1987	Mechanical vibration of rotating electrical machines with shaft heights 56 mm and higher — Measurement, evaluation and limits of vibration severity

3 CHARACTERISTICS OF THE MOTOR

In the case of IGBT converters, knowledge of the motor equivalent circuit is not normally important for the design of the commutating circuit, but the harmonic impedances of the motor greatly influence the losses caused by harmonics.

The above condition is relevant for the basic operation capability of the drive. If details are required of the additional torques (in particular oscillating torques) and of the additional losses, which occur during converter operation, then knowledge of the equivalent circuit parameters of the motor covering the harmonic spectrum will be necessary.

Due to the existing design variants of cage induction motors (for example copper deep bar rotors and aluminium double-cage rotors are used) and due to the wide frequency range of the most important harmonics (band width from 0 up to 30 kHz), a generally valid motor equivalent circuit cannot be specified. As a rule it is not admissible to use the quantities from the equivalent circuit for steady state operation at system frequency (for example with leakage inductances for normal running) in order to calculate torques and losses due to harmonics. The motor manufacturer may provide appropriate values of the equivalent circuit only, if the frequency spectrum of currents and/or voltages generated by the converter is known.

4 FREQUENCY SPECTRUM OF VOLTAGE AND/OR CURRENTS

With respect to the necessary torque derating and to the oscillating torques excited by harmonics, it is important to know the relative harmonic content of motor voltage and/or currents compared with those during operation on a sinusoidal supply voltage.

Figure 1 shows the typical waveform of the motor line-to-line voltage for operation with a synchronized pulse pattern where the harmonics are of the order $n = 5; 7; 11; 13$.

4.1 Harmonic Voltage Factor (HVF)

The harmonic voltage factor (HVF) is defined as follows:

$$\sum_{n=5^{n}}^{n=\infty} V_n^2$$

where

n = order of odd harmonic, not including those divisible by three; and

V_n = per unit magnitude of the voltage at the n^{th} harmonic frequency.

Example: With per unit voltages of 0.10, 0.07, 0.045, and 0.036 occurring at the 5, 7, 11, and 13th harmonics, respectively, the value of the HVF is:

$$0.10^2\ 0.07^2\ 0.045^2\ 0.036^2$$

$$+++=0.054\ 6$$

$$5\ 7\ 11\ 13$$

4.2 Derating for Harmonic Content

Harmonic currents are introduced when the line

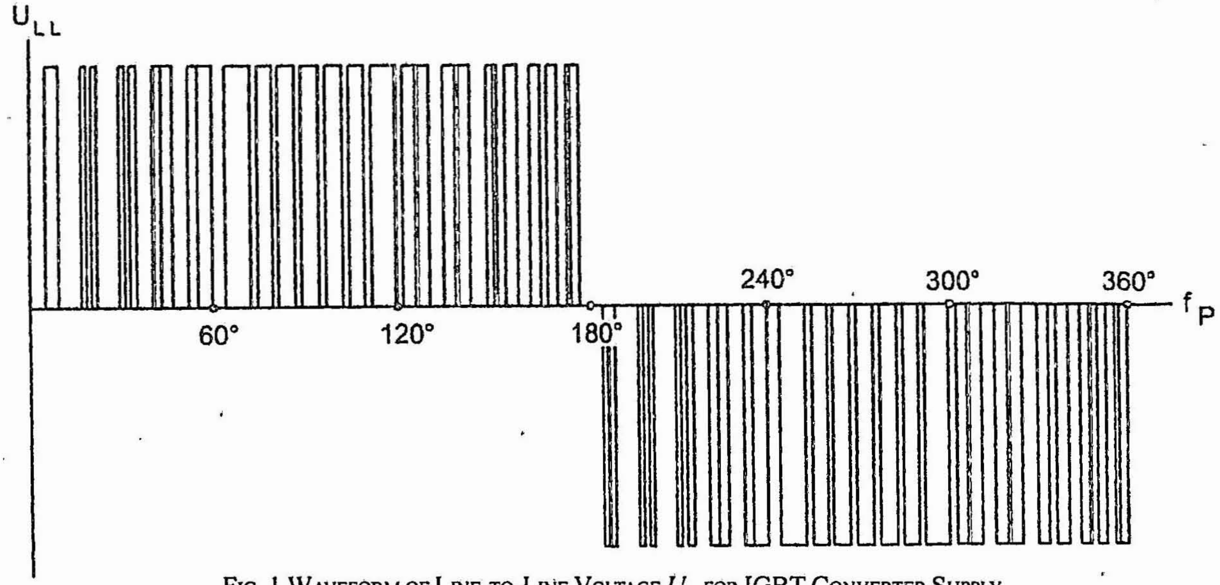


FIG. 1 WAVEFORM OF LINE-TO-LINE VOLTAGE U_{LL} FOR IGBT CONVERTER SUPPLY WITH PULSE FREQUENCY $f_p = 30 \times f_1$ (EXAMPLE)

voltages applied to a three phase induction motor include voltage components at frequencies other than nominal (fundamental) frequency of the supply. Consequently, the temperature rise of the motor operating at a particular load and per unit voltage harmonic factor will be greater than that for the motor operating under the same conditions with only voltage at the fundamental frequency applied.

When a motor is operated at its rated conditions and the voltage applied to the motor consists of components at frequencies other than the nominal frequency, the rated power of the motor should be multiplied by the factor shown in Fig. 2 to reduce the possibility of damage to the motor. This curve is developed under the assumption that only harmonics equal to add multiples (except those divisible by three) of the fundamental frequency are present. It is assumed that any voltage unbalance or any even harmonics, or both, present in the voltage are negligible.

5 ADDITIONAL LOSSES

Harmonics of voltage and current in a cage induction motor supplied from a converter cause additional iron and winding losses in the stator and the rotor.

There is no simple method to calculate the additional losses, and no general statement can be made about their value. Their dependence upon the different physical quantities is very complex. Also there is a great variety both of converters (for example with different pulse frequencies and pulse patterns) and of motors (for example kind of winding, skewing, slot geometry).

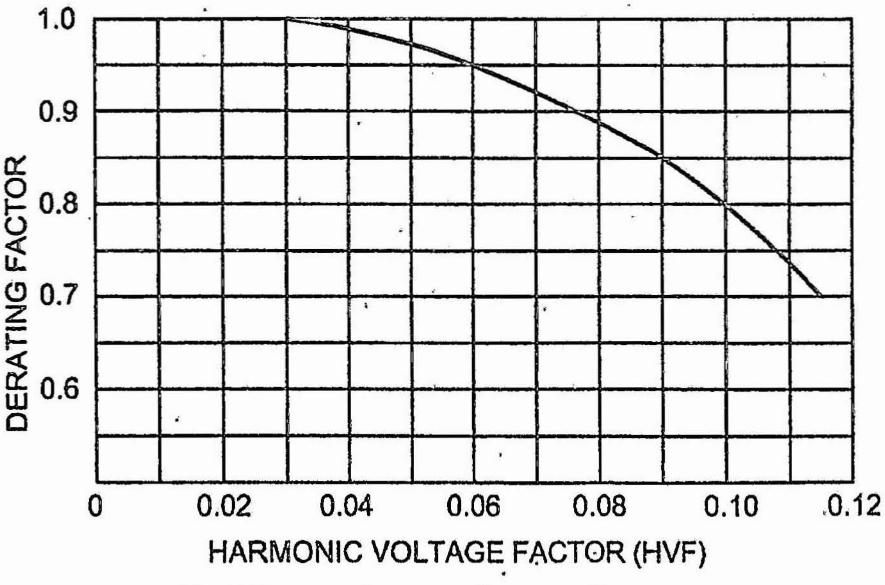


FIG. 2 DERATING CURVES FOR HARMONIC VOLTAGES

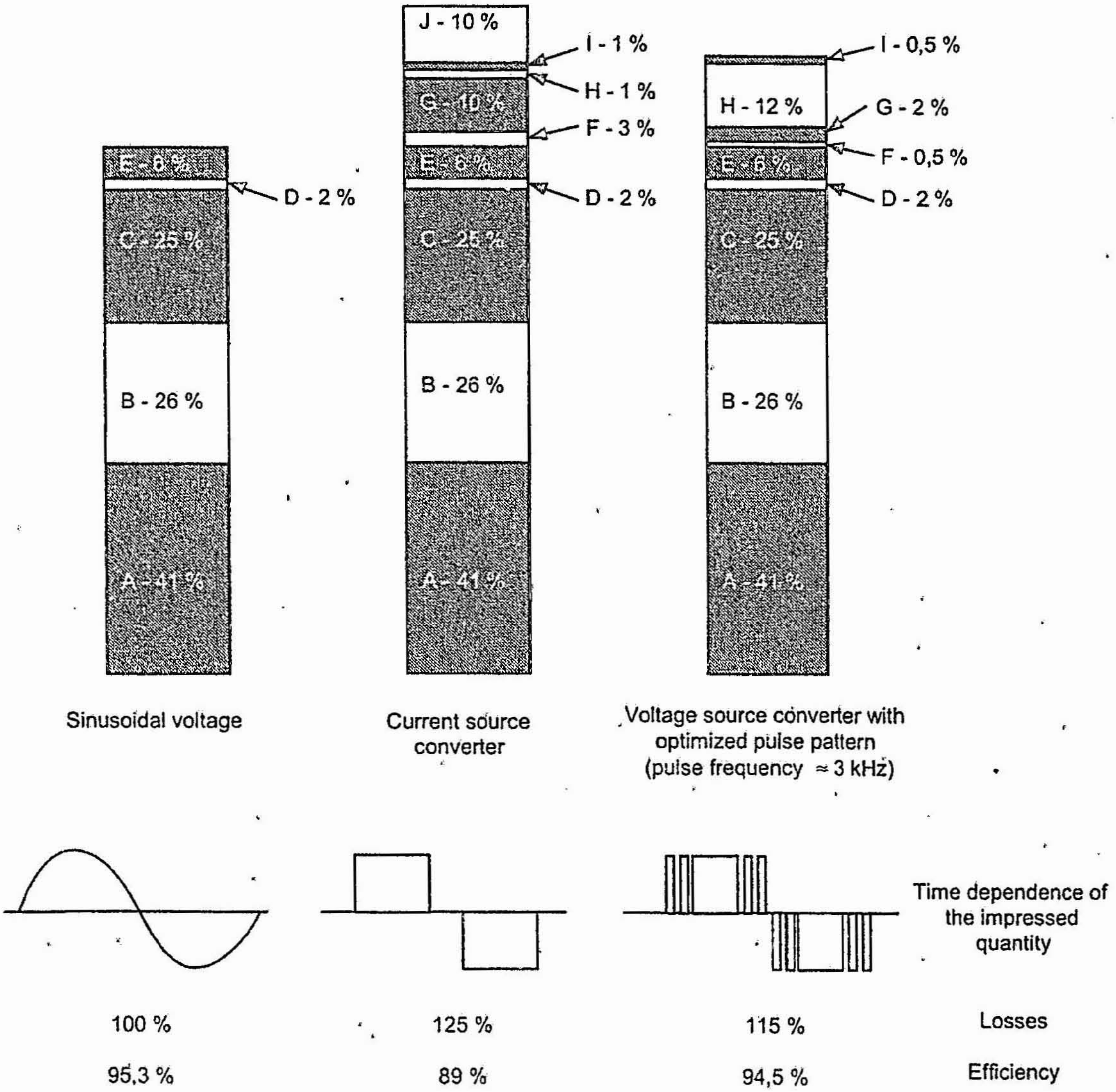
The columns in Fig. 3 show, as an example, the calculated loss composition of a specific motor (frame size 315 M) when supplied both from sinusoidal supply and IGBT converter. The comparison cannot be transferred to other converter-fed cage induction motors and other types of converters (with different pulse frequencies). To facilitate comparison in Fig. 3, the fundamental voltages and currents during converter operation are assumed to be the same as under rated conditions.

5.1 Efficiency

Efficiency will be reduced when a motor is operated with IGBT converter. The harmonics present will increase the electrical losses which, in turn, decrease efficiency. This increase in losses will also result in an increase in motor temperature, which further reduces efficiency.

5.2 Temperature

When the motor is tested with converter supply at



Losses caused by harmonics	Losses caused by fundamental frequency
J – Commutation losses	*E* – Frictional Losses
I – Additional load losses	*D* – Additional load losses
H – Iron losses	*C* – Iron losses
G – Rotor winding losses	*B* – Rotor winding losses
F – Stator winding losses	*A* – Stator winding losses

FIG. 3 INFLUENCE OF CONVERTER SUPPLY ON THE LOSSES OF A CAGE INDUCTION MOTOR (FRAME SIZE 315 M) WITH RATED VALUES OF TORQUE AND SPEED

rated load, base voltage and base frequency, the permissible temperature rise will be within the limits of insulation system used. For example when a motor having Class F insulation system is tested with sinusoidal supply at rated voltage, frequency and rated load, may have temperature rise within Class B limits. However, when the same motor is tested with converter supply under same test conditions, the temperature rise will be within Class F limits. It is assumed that while testing with converter supply, the HVF factor of converter output supply is maximum 3 percent.

It is recommended that the HVF factor is determined prior to temperature rise test.

6 TORQUE

6.1 Motor Torque During Operation Below Base Speed

To develop constant torque below base speed by maintaining constant air gap flux, the motor input voltage is varied to maintain approximately rated volts/hertz. The full line curve in Fig. 4 refers to a converter producing the same fundamental motor flux as a sinusoidal supply.

Frequently, in practice, the converter rating does not imply that the fundamental flux at rated frequency is the same as on sinusoidal voltage. The consequence is an additional torque deviation, the values of which depend on the individual parameters.

Within the speed setting range below the synchronous speed at motor rated frequency, applying a U_1/f_1 = constant law leads to a constant pull-out torque if the stator winding resistance is negligible in comparison with the motor reactances. To compensate for the effect of the motor stator resistance, and to maintain constant air gap flux (that is constant torque), some converters are designed to have a characteristic in accordance with the dash line in Fig. 4. Effectively, this is an increase in the volts per hertz ratio (boost voltage) and is normally provided at frequencies below approximately 50 percent of rated frequency. At low speeds higher torques are generated than in the absence of such compensation. Also, for applications that require less than rated torque below base speed, system economics may be improved by operation at reduced volts per hertz ratio.

6.2 Torque Derating Based on Reduction in Cooling

Induction motors to be operated in converter applications should be derated due to the reduction in cooling resulting from any reduction in operating speed. This derating should be in accordance with Fig. 5. This derating may be accomplished by or inherent in the load speed-torque characteristics, or may require selection of an oversized motor. The curves are applicable only to the standard frame sizes and standard designs and as noted, additional derating for harmonics may be required. For larger frames or special design types, consult the motor manufacturer.

NOTES

1 Deration curve is based on a sinusoidal wave shape, rated air-gap flux. Additional derating for harmonic voltages should be applied as a multiplier to the above limits.

2 Curve is applicable only to motors up to 400 frame sizes and standard designs. For larger frames or other design types consult the motor manufacturer.

6.3 Torque Derating During Control Operation

Induction motors to be operated on adjustable-speed drive applications should also be derated as a result of the effect of additional losses introduced by

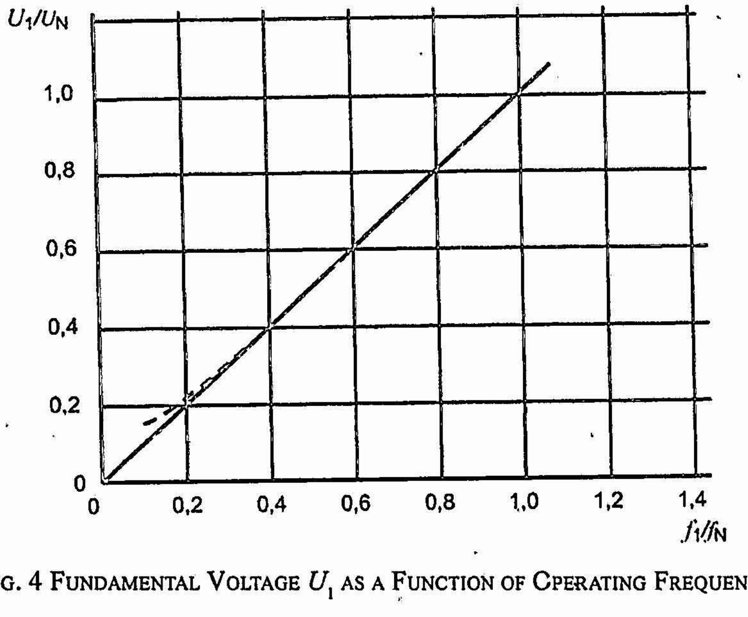


FIG. 4 FUNDAMENTAL VOLTAGE U_1 AS A FUNCTION OF OPERATING FREQUENCY f_1

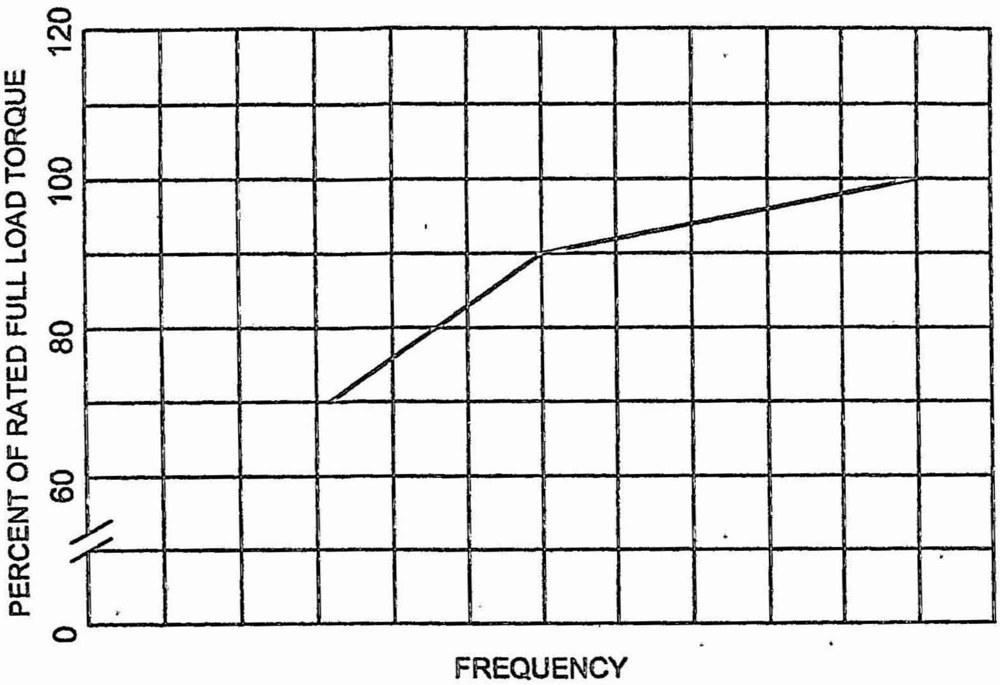


FIG. 5 THE EFFECT OF REDUCED COOLING ON THE TORQUE CAPABILITY AT REDUCED SPEEDS OF 50 Hz STANDARD DESIGN MOTORS

harmonics generated by the converter. The torque available from the motor for continuous operation is usually lower than on a sinusoidal voltage source. The reduction results from the additional temperature rise due to harmonic losses and also from the voltage-frequency characteristics of converters.

The temperature rise at any load-speed point depends on the individual motor design, the type of cooling, the effect of the reduction in speed on the cooling, the voltage applied to the motor, and the characteristics of the converter (for example harmonic spectrum of the converter and HVF factor). When determining the derating factor, the thermal reserve of the particular motor is important. Taking all of these matters into account, the derating factor at rated frequency ranges from 0 to 20 percent.

Figure 6 shows example of a derating curve for a typical motor for which the thermal reserve of the motor at rated frequency is less than the additional temperature rise resulting from operation on a converter. It is not possible to produce a curve which applies to all cases. Other motors with different

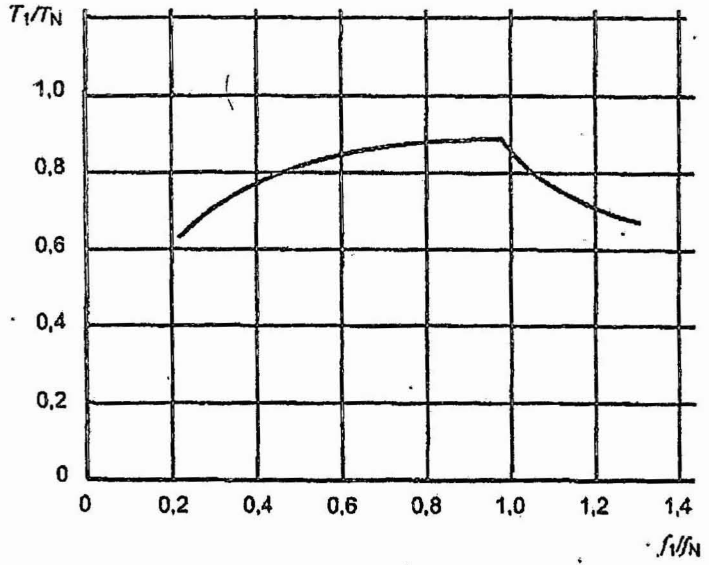


FIG. 6 EXAMPLES OF TORQUE DERATING OF MOTORS WHEN USED W 0.51.0 (p.u.) WITH CONVERTORS

thermal reserve, different methods of cooling (self-circulation cooling or independent cooling), and used with other types of controls will have different derating curves.

In general, however, motors supplied from IGBT (pulse frequency in the kHz range) require smaller torque reductions than those supplied from block converters. The derating is normally reduced as the pulse frequency increases.

There is no established calculation method for determining the derating curve for a particular motor used with a particular control that can be used by anyone not familiar with all of the details of the motor and control characteristics. The preferred method for determining the derating curve for a class of motors is to test representative samples of the motor design under load while operating from a representative sample of the converter design and measure the temperature rise of the winding.

6.4 Motor Torque During Operation Above Base Speed

Above base speed, as frequency increases, a motor with constant input voltage will result in constant power operation (torque reducing with reduced volts per hertz). This constant input voltage is having a fundamental component equal to rated motor voltage (which may be limited by the converter and its input power).This is also called as operation in field weakening range. In the event of this occurring within the frequency operating range, then the derating factor will change with a rapid reduction in Fig. 4 above $f_1/f_N = 1{,}0$. The maximum (breakdown) torque capability of the motor within this speed range will limit the maximum frequency (and speed) at which constant power operation is possible.

The curves in Fig. 7 represent the load which the defined motor is capable of carrying above base speed. The curve represent operation at constant power. The maximum frequency of 1.5 times rated frequency is established based on the approximate peak torque capability of greater than 175 percent for standard design motors, assuming operation at a constant level of voltage equal to rated voltage from rated frequency to 1.5 times rated frequency. For the capability of motors for which the minimum

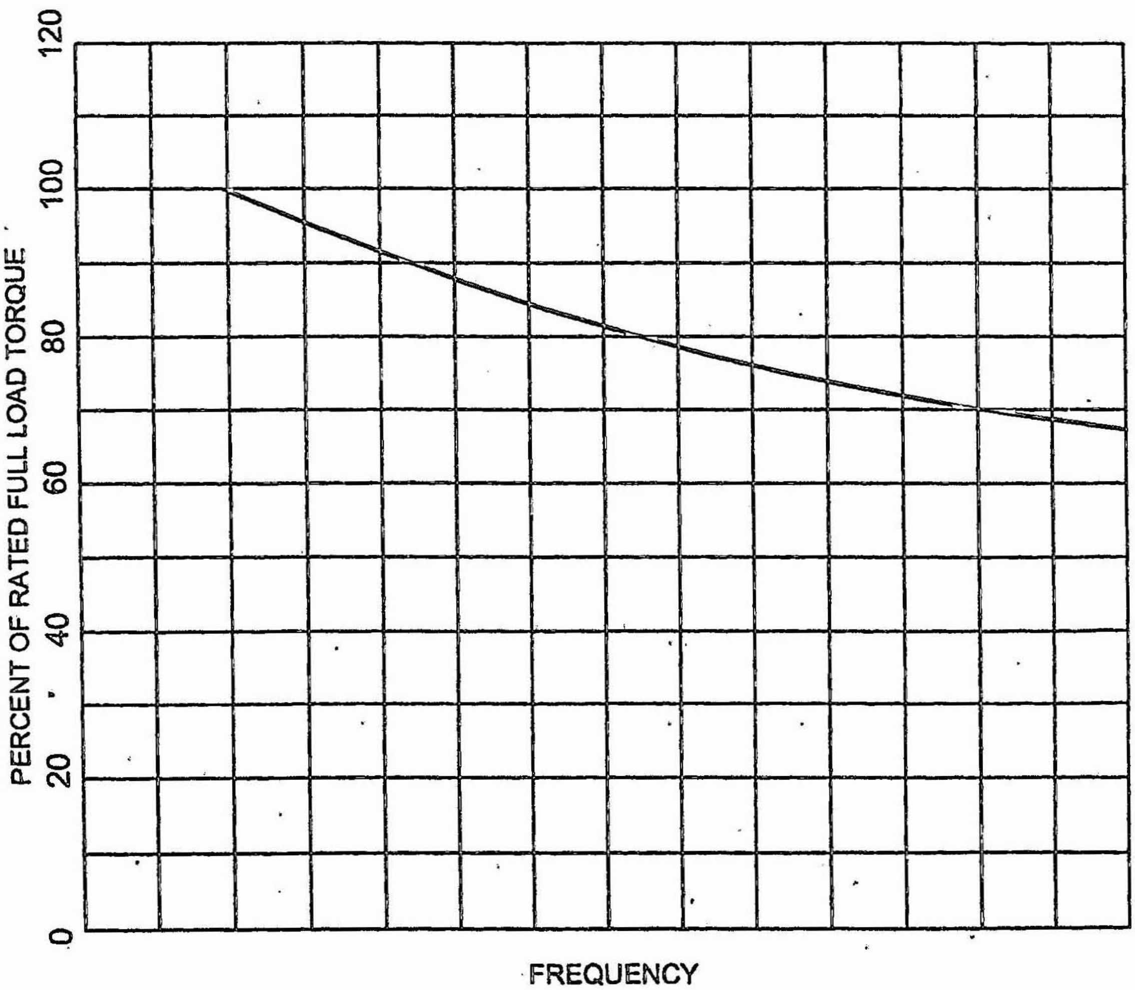


FIG. 7 TORQUE CAPABILITY ABOVE BASE SPEED

breakdown torque is less than 175 percent, consult the motor manufacturer.

For operation above 1.5 times rated frequency at a required power level, it may be necessary to utilize a motor with a greater kW rating at rated frequency.

However, the maximum speed at which a motor can safely operate may be limited to some speed below the maximum speed related to its load carrying capability because of mechanically considerations (*see* 14).

NOTES

1 Limit for Class B 80°C or Class F 105°C rise by resistance.

2 Curve is based on a sinusoidal wave shape, constant voltage equal to rated voltage. Additional derating for harmonic voltages should be applied as a multiplier to the above limits.

3 Curves are applicable to standard design motors having breakdown torques of not less than 175 percent at rated frequency.

4 *See* 14 for any additional limitations on the maximum operating speed.

7 CURRENT

7.1 Running Current

Controls are generally rated in terms of a continuous output current capability, a short term output current, and a peak output current. To properly choose the size of control required in an application, consideration should be given to the peak and transient values in addition to the rms value of motor current, and the manner in which the system is to be operated. Because some level of current will exist at each of the harmonic frequencies characteristic of the particular type of control, the total rms sum of current required by the motor at full load may be from 5 percent to 10 percent greater than that level of current corresponding to operation on a sinusoidal power source. The magnitude of the peak values of the current waveform may vary from 1.3 to 2.5 times the rms value of the current, depending on the type of control considered and the motor characteristics. An additional margin from 10 percent to 50 percent in the current rating of the control should be considered to allow for possible overload conditions on the motor so as not to trip the control on such short time overcurrent demand. When the motor and control are used in a system where sudden changes in load torque or frequency might occur, the control should be sized based on the peak value of the transient current which results from the sudden change. Also, when changing from one operating speed to another, if the rate of change in frequency is greater than the possible rate of change in motor speed and if the slip increases beyond the value of slip at rated load, then the amount of rms current or peak current required from the control may exceed that of the steady state requirements.

7.2 Starting Current

In a stall condition, the magnitude and frequency of the applied voltage and the impedance of the motor primarily determine the amount of current drawn by an induction motors. Under adjustable frequency control, motors are normally started by applying voltage to the motor at a low frequency (less than 3 Hz). The current drawn by the motor under this condition is mainly a function of the equivalent stator and rotor resistances since the reactive impedance is small because of the low frequency. In order to provide sufficient starting torque, it is necessary to provide an increase in voltage (voltage boost) at low frequencies in order to overcome this resistive drop in the motor. This voltage boost is the product of the required phase current (for the level of breakaway torque needed) and the stator phase resistance and the square root of 3 (to convert phase quantity to line-to-line value). A wye connection is assumed. For rated torque at start it will be necessary to adjust the voltage boost to have at least rated current. Since stator and rotor resistances vary with temperature, the actual starting current will be a function of the machine temperature.

Continued application of boosted motor voltage at low frequencies under no load conditions will increase motor heating. When voltage boost is required to achieve a breakaway torque greater than 140 percent of rated torque, the motor should not be operated under voltage boost condition at frequencies less than 10 Hz for more than 1 min without consulting the manufacturer.

8 RESONANCE AND OSCILLATING TORQUES

The asynchronous (time-constant) torques generated by harmonics have little effect on the operation of the drive. However, this does not apply to the oscillating torques, which produce torsional vibrations in the mechanical system.

When an induction motor is operated from a control, torque ripple at various frequencies may exist over the operating speed range. Consideration should be given to identifying the frequency and amplitude of these torques and determining the possible effect upon the motor and the driven equipment. It is of particular importance that the equipment not be operated longer than momentarily at a speed where a resonant condition exists between the torsional system and the electrical system (that is the motor electrical torque). For example, if the control is of the six step type than a sixth harmonic torque ripple is created which would vary from 36 to 360 Hz when the motor is operated over the frequency range of 6 to 60 Hz. At low speeds, such torque ripple may be apparent as observable oscillations of the shaft speed or as torque and speed pulsations (usually termed 'cogging'). It is also possible that some speeds within the operating range may correspond to the natural mechanical frequencies of the load or support structure and operation other than momentarily could be damaging to the motor and/or load and should be avoided at those speeds.

In drives with IGBT converters, the frequencies of the dominant oscillating torques are determined by the pulse frequency while their amplitudes depend on the pulse width. Thus the oscillating torque amplitudes may be as high as 15 percent, provided that the pulse frequency exceeds 10 times the fundamental frequency, which is usually the case in today's converters. With higher pulse frequencies (in the order of 21 $\times f_1$) the oscillating torques of frequencies 6 $\times f_1$ and 12 $\times f_1$ are practically negligible, provided a suitable pulse pattern is applied (for example modulation with a sinusoidal reference wave or space-phasor modulation). Additionally, oscillating torques of twice the pulse frequency are generated. These, however, do not exert detrimental effects on the drive system since their frequency is far above the critical mechanical frequencies.

9 MAGNETICALLY EXCITED NOISE

Due to harmonics, the excitation mechanism for magnetic noise becomes more complex than for operation on a sinusoidal supply. A reliable precalculation of magnetic noise which occurs during converter operation of cage induction motors is not possible at present. In particular, resonance may occur at some points in the speed range.

Sound levels are higher when using induction motors with IGBT converter. The sound level is dependent upon the construction of the motor, the number of poles, the pulse pattern and the pulse frequency, and the fundamental frequency and resulting speed of the motor. The response frequencies of the driven equipment should also be considered. Sound levels produced thus, are higher than published values when operated above rated speed. At certain frequencies, mechanical resonance or magnetic noise may cause a significant increase in sound levels, while a change in frequency and/or voltage may reduce the sound level.

When supplying a motor by IGBT converter, additional magnetically excited tones are generated by the voltage harmonics. The frequencies are close to the pulse frequency of the converter or multiples of it and can be close to the natural frequencies of the active parts of the stator. The amplitudes of the noise exciting forces vary much with the control strategy of the converter. When the pulse frequency is fixed, there are high spikes in the spectrum. By contrast, when the pulse pattern is controlled online, practically no spikes are visible in the spectrum. Therefore the A-weighted noise level increase varies more widely compared with operation on a sinusoidal supply at rated voltage and rated frequency than for current source converter supplied motors. According to experience the increase at constant flux (at rated voltage and frequency) is likely to be in the range 1 dB to 15 dB. For other frequencies, the noise levels may be higher.

10 SERVICE LIFE OF THE INSULATION SYSTEM

The insulation system of the motor is subjected to higher dielectric stresses than in the case of supply with sinusoidal voltages and currents. The voltage gradients, which stress the interturn insulation, particularly, that of the line coils, are of importance in the case of supply from IGBT converters.

The dielectric stress of the winding in insulation is determined by the peak voltage, rise time and frequency of the impulses produced by the converter, the characteristics and the length of the connection leads between the converter and motor, the winding construction and other system parameters. Especially the voltages between the different parts of the winding and the ground represent a significant basis of evaluation.

Motors with random wound windings with enamelled round wires will typically endure the pulse voltages of Fig. 8 at the terminals without significant reduction of lifetime.

The combination of fast switching inverters with cables will cause peak voltages due to transmission line effects. For motors rated at voltages less than or equal to 500 V ac the insulation system should typically give satisfactory life when subjected to peak voltages shown in Fig. 8.

For motors rated over 500 V ac up to 690 V ac, supplied from a fast switching inverter, an enhanced insulation system and/or filters designed to limit the rise time and/or peak voltages may be required.

The term rise time is based on the following definition which takes into account the transient phenomena within the winding (*see* Fig. 9).

The voltages range Δu is the difference between the instantaneous values of the voltage directly before and after the voltage impulse. This impulse is finished at the instant when the voltage has reached its first maximum. The rise time t_a is defined as the interval during which the voltage changes from 10 percent to 90 percent of the whole voltage range Δu.

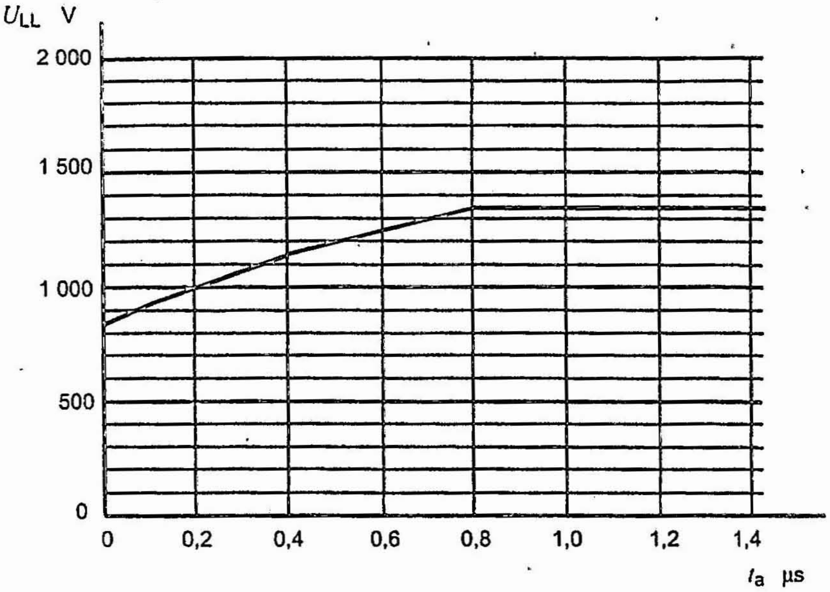


FIG. 8 LIMITING CURVE OF ADMISSIBLE IMPULSE VOLTAGE U_{LL} (INCLUDING VOLTAGE REFLECTION AND DAMPING) AT THE MOTOR TERMINALS AS A FUNCTION OF THE RISE TIME t_a

In view of the complex interrelations, a careful design of the complete drive is suggested. Sometimes the use of filters at the converter output is necessary.

11 BEARING CURRENTS

During converter operation bearing currents may be caused by two different kinds of voltages.

11.1 Shaft Voltage

The term shaft voltage is applied to a voltage, which is induced in the conducting loop comprising the shaft, the bearings, the end shields and the housing (*see* Fig. 10), by a ring flux in the stator yoke. Irregularities within the yoke (for example dovetailed punchings to clamp the core, ventilation ducts, magnetic anisotropies of the laminations) may cause a ring flux. The ring flux may be increased by a zero-sequence component of the stator currents (so-called common mode currents), the magnitude of which depends on the earthing system of the motor. A

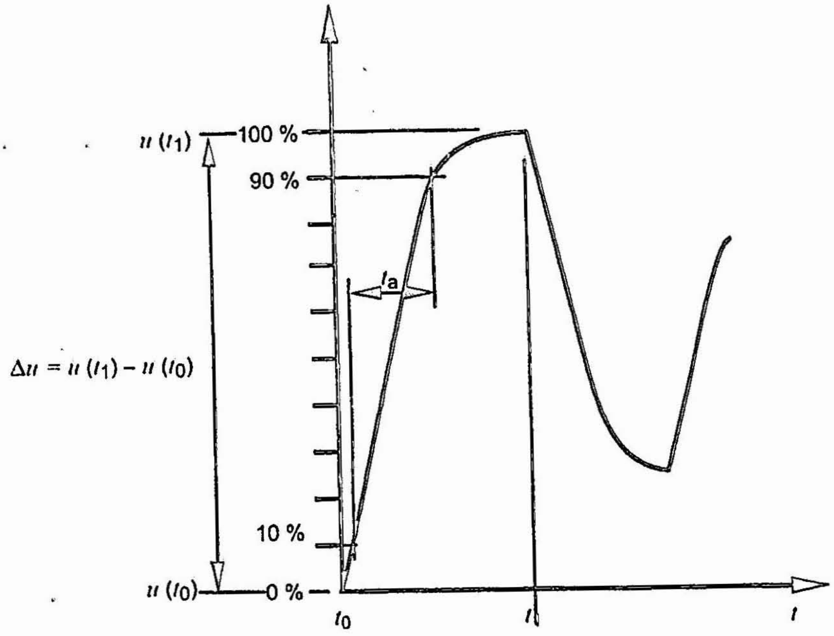


FIG. 9 DEFINITION OF THE RISE TIME t_a OF THE VOLTAGE AT THE MOTOR TERMINALS

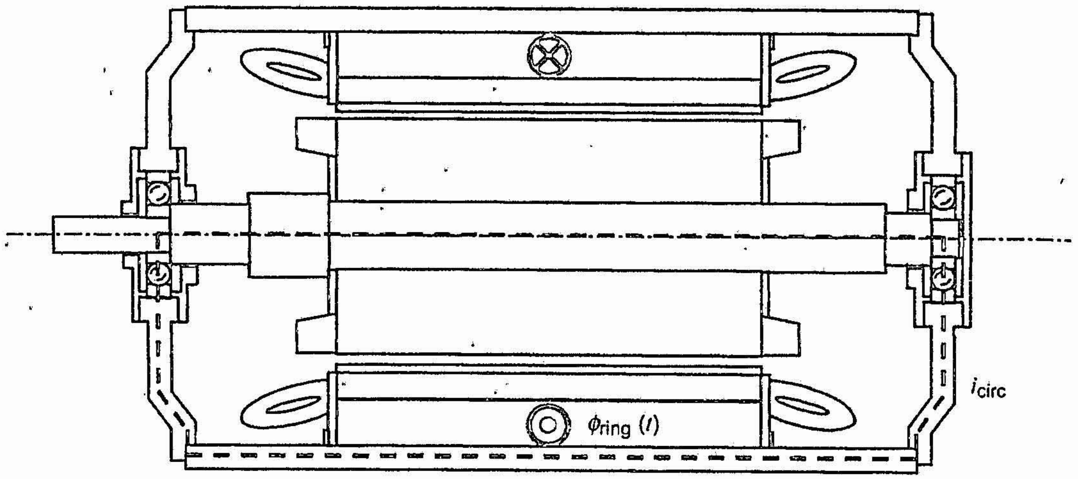


FIG. 10 RING FLUX INCLUDING SHAFT VOLTAGE AND RESULTING CIRCULATING CURRENT i_{circ} BEARING VOLTAGE

current spike appears at all instants, when one of the semiconductor elements is switched, generally six-times per period of the pulse frequency.

The term bearing voltage is applied to a capacitively coupled voltage at the radial clearance of the bearing (*see* Fig. 11). The bearing voltage is caused originally by an alternating voltage between the mean potential of the stator winding and the grounded stator core (so-called common mode voltage), which is inherent to the control algorithm of IGBT converters. The common mode voltage consists in particular of components of three-times the system frequency, of three-times the basic frequency at the output terminals of the converter and of the pulse frequency. Its peak value is in the range of 50 percent of the dc voltage in the intermediate circuit of the converter. Depending on the capacitances between the stator winding and the rotor, between the rotor and the housing and the capacitance of the bearing itself, a specific percentage of the common mode voltage can be measured at the radial clearance of the bearings. Thus the time characteristic of the bearing voltage is a replication of the common mode voltage.

If it is intended to measure the shaft voltage or the bearing voltage during converter operation, appropriate precautions should be taken and specific instrumentation and shielded measuring cables have to be used.

When operating a motor at sinusoidal voltage, the bearing voltage is practically zero. If the shaft voltage does not exceed approximately 500 mV (peak), no protective devices are necessary according to experience of long standing. Shaft voltage above approximately 500 mV (peak) may produce circulating currents in the conducting loop indicated above, which may destroy the bearings within a relatively short period of time. Insulation of one bearing, preferably at the non-drive end, is sufficient to avoid circulating currents through both bearings and eventually through bearings of the driven equipment.

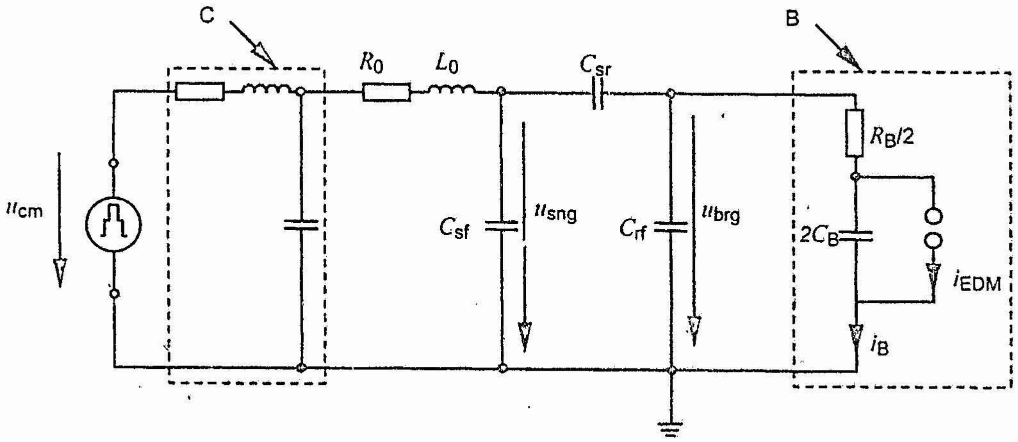


FIG. 11 COMMON MODE CIRCUIT MODEL AND BEARING VOLTAGE u_{brg}

The insulation of bearings is neither necessary nor customary in case of motors within the scope of this specification, when operated at sinusoidal supply voltage and fabricated according to the current state of the art.

During IGBT converter operation, shaft voltage and bearing voltages exist simultaneously. High gradients of the bearing voltage may result in capacitive bearing currents (so-called *du*/*dt* currents). In addition short-time discharging currents (so-called EDM currents) arise if the bearing voltage exceeds its breakdown value. The repetition rate of the EDM currents increases with increasing values of bearing voltage and pulse frequency. Both kinds of currents caused by bearing voltage flow along the path of the capacitances indicated above respectively along the grounding system of the motor, but not through both bearings (EDM = electrostatic discharge machining).

Depending on the pulse frequency, the rise time of the pulses and the motor rating, the shaft voltage contains peak of high frequency, possibly in excess of 10 V which may cause the puncture of the lubrication film of the bearings. But the component of fundamental frequency produces an emf. Thus the frequency spectrum of the circulating currents predominantly contains the fundamental frequency and its 3rd harmonic. The current flow may be sustained by the component of fundamental frequency, even when its amplitude is less than 500 mV (peak), in so far as a motor with low shaft voltage at sinusoidal supply is advantageous to avoid circulating currents at converter supply.

According to measurements, typically the bearing voltage is in the range of 10 V to 30 V (peak). An interrelation between circulating currents and bearing voltage could not be recognized.

Experience shows:

a) Motors within the scope of this specification and with frame numbers up to and including 315 seldom experience-bearing failure caused by converter operation. Nevertheless the dielectric stress on the bearings varies widely with the type of the control algorithm of the converter. However when using converters having a pulse frequency greater than 10 kHz and an output voltage greater than 400 V rms, consideration should be given to the use of bearing insulation.

b) For machines within the scope of this specification and with frame numbers above 315, it is recommended either;

   i) To use a converter with a filter designed to reduce the zero-sequence. To use a converter with a filter designed to reduce the zero-sequence; or

   ii) to reduce the *du*/*dt* of the voltage; and/or

   iii) to insulate the motor bearing(s).

c) The insulation of a ball bearing can be achieved by replacement with an insulated bearing of the same dimensions. The need to insulate both motor bearings is seldom necessary. In such a case the examination of the whole drive system by an expert is highly recommended and should include the driven machine (insulation of the coupling) and the grounding system (possibly use of an earthing brush).

12 LONG CABLES

When the motor is at a long distance from the converter, the cable connecting the motor to the converter acts like a transmission line with the equivalent circuit shown in Fig. 12. The inductance is the phase inductance per unit length, and the capacitance is the line-to-ground capacitance per unit length.

From transmission line theory, when the line impedance is less than the load impedance, voltage and current waves are reflected, and the voltage is largest at the load. This is the case for drive applications. The motor surge impedance is often several times the value of cable characteristic impedance. Therefore the reflection coefficient approaches to unity and reflected wave has peak of two times DC bus voltage. Although the mismatch between cable and motor impedance is highest for small motors, in all cases, voltage is greatest at the motor.

The reflection coefficient is:

$$P = \frac{Z_m - Z_c}{Z_m + Z_c}$$

where

Z_m = motor surge impedance, and

Z_c = surge impedance of the cable to travelling waves.

$V'_a = (1+P) \times V\text{a}$

The voltage at the motor is the sum of the incident and reflected waves. For motors smaller than about 18.5 kW, the reflection coefficient is 1.0. For long cables, voltage doubling occurs at the motor terminals.

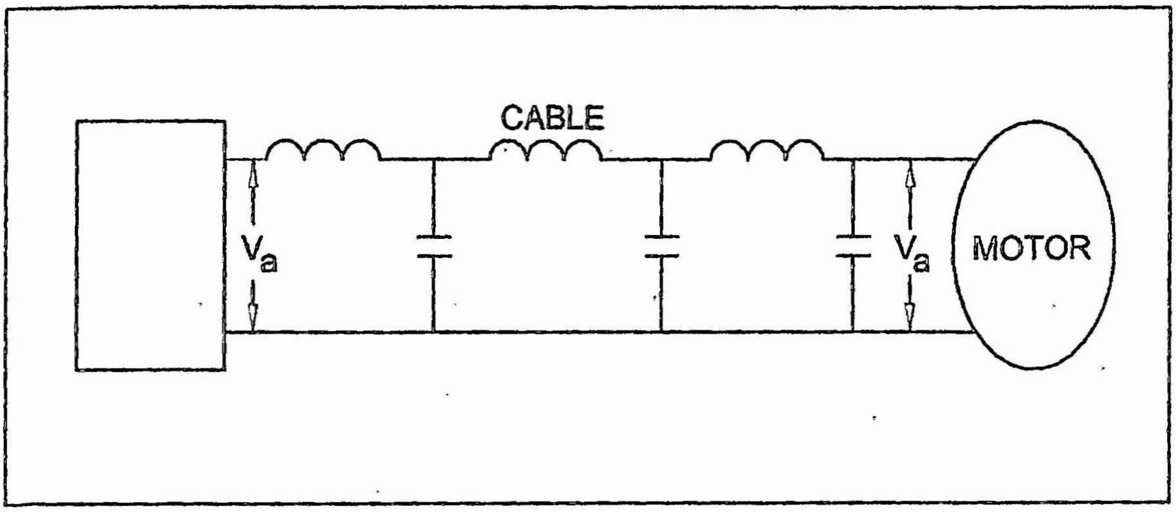


FIG. 12 EQUIVALENT TRANSMISSION LINE CIRCUIT

13 CRITICAL CABLE LENGTH

The critical cable length is the maximum cable length at which voltage amplification does not occur. It is the length at which the sum of the reflected and incident waves is equal to the peak value of the incident wave. Voltage at the motor terminals increases as cable length increases beyond critical cable length.

If the propagation speed of the voltage wave is S and the rise time of the IGBT converter wave front (defined as the time taken for the output to go from 10 percent to 90 percent of its peak value) is T, then the distance traveled by the wave front during its rise time is $S \times T$. If the motor is at a position where the incident wave has just reached 50 percent of its full value and if the reflection coefficient is 1.0, then the sum of the reflected and incident waves will yield 100 percent of the peak value of the incident wave. Any distance greater than this critical cable length would result in a voltage greater than 1.00 per unit. So the critical cable length is given by:

$$\frac{S \times T}{2}$$

The propagation speed over a conductor depends on its inductance and capacitance per unit length and can be expressed as:

$$S = \frac{1}{\sqrt{LC}}$$

Typical values for propagation speed range from 100 to 150 m/μs.

Table 1 lists critical cable lengths with a propagation velocity of 100 m/μs for rise times ranging from 2 μs to .05 μs. The rise time of the voltage wave is controlled by how quickly the power semiconductors in the converter are turned on. Typical rise times for power semiconductors used in converters range from .05 to .50 μs.

Table 1 Critical Cable Length for Various Rise Times

Sl No.	Rise Time μs	Critical Lead Length m
(1)	(2)	(3)
i)	2.00	100
ii)	1.0	50
iii)	0.50	25
iv)	0.10	5
v)	0.05	2.5

When using higher cable lengths, it is advisable to use a lower switching frequency and *dv*/*dt* filters.

14 MAXIMUM SAFE OPERATING SPEED

If a motor is intended to be operated at speeds above its rated speed, the maximum safe operating speed of a direct coupled motor at 0° to 40°C ambient temperature should not exceed the values given in the following table. Depending on the motor design, the operation at higher speeds for conditions other than stated may be allowable, but this possibility should be verified by the motor manufacturer.

When operating at speeds above rated speed, noise and vibration levels will increase. It may also be required to refine the balance for acceptable operation above rated speed.

Operation at speeds close to the maximum safe operating speed for extended periods of time may cause considerable shortening of the service life of the bearings. Moreover, the shaft seals and/or the regreasing intervals (or the grease service life in the case of greased-for-life bearings) may be affected.

NOTES

1 The permissible overspeed value is 20 percent above values in Table 2 (not to exceed 2 min in duration).

2 The values in Table 2 are based on mechanical limitations. Within the operating limits noted in Table 2, the motor is capable of constant power from rated frequency to approximately 1.5 times rated frequency. Above approximately 1.5 times rated frequency, the motor may not provide sufficient torque based on specified voltage to reach stable speeds while under load.

3 Operation above nameplate speed may require refined balance.

4 Considerations:

- a) Noise limits as per IS 12065 and vibration limits as per IS 12075 are not applicable.
- b) Bearing life will be affected by the length of time the motor is operated at various speeds.

15 POWER FACTOR CORRECTION

The use of power capacitors for power factor correction on the load side of an electronic power supply connected to an induction motor is not recommended. The proper application of such capacitors requires an analysis of the motor, electronic power supply and load characteristics as a function of speed to avoid potential over-excitation of the motor, harmonic resonance and capacitor over voltage. For such applications the drive manufacturer should be consulted.

16 OPERATION IN HAZARDOUS (CLASSIFIED) LOCATIONS

Motors operated from adjustable frequency or adjustable voltage power supplies or both, should not be used in any Division 1 hazardous (classified) locations unless the motor is identified on the nameplate as acceptable for such operation when used in Division 1 hazardous (classified) locations.

For motors to be used in any Division 2 hazardous (classified) locations, the motor manufacturer should be consulted.

Failure to comply with this warning could result in an unsafe installation that could cause damage to property or serious injury or death to personnel, or both.

Table 2 Maximum Safe Operating Speeds for Direct-Coupled Motors Used on IGBT Converters

(*Clause* 14)

Sl No. (1)	Flame Number (2)	2 Pole (3)	4 Pole (4)	6 Pole (5)
i)	112	5 200	3 600	2 400
ii)	132	4 500	2 700	2 400
iii)	160	4 500	2 700	2 400
iv)	180	4 500	2 700	2 400
v)	200	4 500	2 300	2 400
vi)	225	3 600	2 300	1 800
vii)	250	3 600	2 300	1 800
viii)	280	3 600	2 300	1 800
ix)	315	3 600	2 300	1 800

NOTE — The above value may have to be reduced to meet the requirements of flameproof motors.

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Rotating Machinery Sectional Committee, ETD 15

FOREWORD

This Indian Standard was adopted by the Bureau of Indian Standards, after the draft finalized by the Rotating Machinery Sectional Committee had been approved by the Electrotechnical Division Council.

The performance characteristics and operating data for drives with converter-fed cage induction motors are influenced by the complete system, comprising supply system, converter, induction motor, mechanical shafting and control equipment. Each of these components exists in numerous technical types. Any values quoted in this standard are thus indicative only.

In view of the complex technical interrelations within the system and the variety of operating conditions, it is beyond the scope and object of this standard to specify numerical or limiting values for all the quantities, which are of importance for the design of the drive.

To an increasing extent it is practice that drives consist of components produced by different manufacturers. The object of this standard is to explain and quantify, as far as possible, the criteria for the selection of components and their influence on the performance characteristics of the drive.

Motor Categories

There are two categories of cage induction motors, which can be applied in variable speed electric drive systems:

a) Standard cage induction motors, designed for general-purpose applications. The design and performance of these motors are optimized for operation on a fixed frequency sinusoidal supply. Nevertheless, they are generally also appropriate for use in variable speed drive systems.
b) Cage induction motors specifically designed for converter operation. The design and construction of such motors may be based on standard motors with standardized frame sizes and dimensions, but with modifications for converter operation

Guidance on this field of application is given in this standard.

This category is covered by IS 15881 : 2009 'Three phase cage induction motors specifically designed for IGBT converter supply — Specification'.

While preparing this standard, necessary assistance has been derived from IEC 60034-17 'Rotating electrical machines — Part 17: Cage induction motors when fed from converters — Application guide'.

For the purpose of deciding whether a particular requirement of this standard is complied with, the final value, observed or calculated, expressing the result of a test or analysis, shall be rounded off in accordance with IS 2 : 1960 'Rules for rounding off numerical values (*revised*)'. The number of significant places retained in the rounded off value should be the same as that of the specified value in this standard.